1. Science aim/goal: Observe gas-phase water in interstellar clouds and dense star-forming cores to probe critical processes related to formation and transport of water to the terrestrial planet zone, as a key input to habitability.

2. (i) Scientific Importance: Our understanding of star and planetary system formation has progressed enormously in recent years, but many important questions remain unanswered. The submillimeter rotational transitions of the water molecule have been demonstrated by Herschel observations to be powerful tools to address a broad range of key questions. Some of these, together with some proposed observational approaches are:

- Where and how is water formed in the interstellar medium and how do the processes controlling the distribution of gas-phase and grain-surface water work?
  - Gas-phase chemistry predicts a high abundance of water, which has shown NOT to be the case in the dense interstellar medium. The generally accepted explanation is that water is largely frozen on the surfaces of dust grains. But the processes and rates for depletion of gas phase atoms and molecules, the surface chemistry, and desorption processes remain highly uncertain.
  - Shocks and outflows produce copious gas-phase water in warm, active environments, but what processes control the water formation on interstellar grain surfaces and what is the interplay between grain-surface ices and the gas phase in cold, quiescent regions?
- What is the velocity field in collapsing dense cores that are on the verge of forming new stars?
  - Water, being kept in the gas phase at a low abundance by cosmic-ray produced UV photons, is a uniquely powerful tracer of kinematics of the inner parts of dense cores, due to its high excitation requirement, even when radiative trapping is considered. This offers an important way to understand the core collapse phase of star formation.

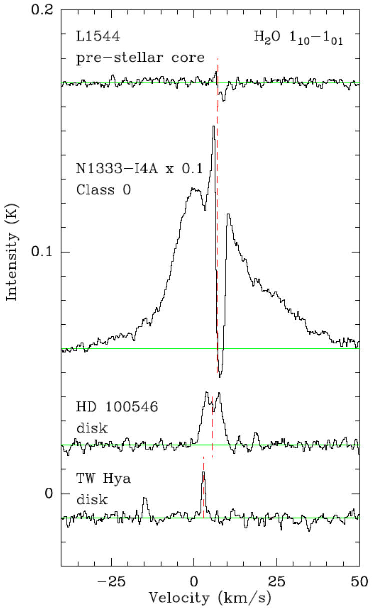
The critical low-energy lines of water from sources in the Milky Way and nearby galaxies cannot be observed at all even from airplane altitudes, so SOFIA's relatively large telescope is not available. Even from a balloon at 39 km, a velocity shift > 50 km/s is required to move away from terrestrial H_2O absorption. Without a space mission incorporating a relatively large telescope, there will be essentially no progress on these questions depending on observations of gas-phase water. The FIR Surveyor, with sufficient sensitivity and a high-resolution spectrometer covering the appropriate frequencies, can enable enormous progress.

(ii) Measurements Required: The measurements required to address the questions given above are high spectral resolution observations of spectral lines in the range 500 GHz to 1113 GHz (600 μm to 270 μm), ideally supplemented by water and other spectral lines at shorter wavelengths. The critical parameter is sensitivity, which is largely controlled by the effective area of the telescope, and to lesser extent angular resolution, which also improves with a larger diameter. The critical values depend on the question being addressed, but a larger collecting area, by a factor ~10 compared to Herschel, is required to, and will make a significant advance in these studies. Higher angular resolution would certainly be valuable if coupled with adequate sensitivity.

(iii) Uniqueness to 10μm to few mm wavelength facility: Only observations of the low-energy rotational transitions of water (including isotopologues) can answer these questions due to the low temperature of the sources of interest - clouds, cores, or outer portions of disks.

(iv) Longevity/Durability: (with respect to expected 2025-2030 facilities)

Water studies with the FIR Surveyor will be highly complementary to ALMA observations of disks, in that rotation curve from ALMA can be used to "deconvolve" H_2O spectra and determine the location of the water emission in the disk. FIR Surveyor observations of gas-phase water will complement studies of ices made with JWST. Improved understanding of the water trail from the ISM to planets will be highly synergistic with studies of exoplanet atmospheres that will be carried out with JWST or EELT. Thus overlap with all these facilities is highly desirable.



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3. Figure: Herschel-HIFI spectra of the H_2O 1_{10}-1_{01} line at 557 GHz in a prestellar core (top), a protostellar envelope (middle), and two protoplanetary disks (bottom). The red dashed line indicates the systemic velocity of the source. The feature at -15 km/s in the TW spectrum is due to NH_3. From van Dishoeck et al. (2014).

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	µm	600 - 270	to 100 µm	548, 557, 988, 995, 1107, 1113 GHz (H_2O & isotopologues); higher lines up to 4000 GHz add value in highly-excited regions
Number of targets		120	260	includes clouds, cores, disks, comets, other Solar System objects
Survey area	deg.^{2}			NA
Angular resolution	arcsec	30	10	At 550 GHz, but smaller beam desirable for detailed imaging of sources
Spectral resolution	λ/Δλ	5x10^6	10^7	0.06 km/s minimum
Bandwidth	Hz	3x10^8	10^9	max.; scales w. frequency
Continuum Sensitivity (1σ)	Jy			NA
Spectral line sensitivity(1σ)	W m^{-2}	1x10^{-19}	1x10^{-20}	4 mK in 1 km/s @ 600 GHz = 1x10^{-19}
Signal –to-noise				NA
Dynamic range				NA
Field of Regard				Few min. arc for focal plane arrays
Cadence				NA
Any other req.				Ability to track Solar System objects

5. Key references:

van Dishoeck, E., Bergin, E., Lis, D., & Lunine, J. 2014, Protostars and Planets VI, 835
Keto, E., Caselli, P., & Rawlings, J. 2014, MNRAS, 446, 3731

APPENDIX

A-1 Water as a Probe of the ISM

Gas phase chemical models of dense, well-shielded interstellar clouds predict that water would be one of the major chemical constituents, following closely behind CO as a reservoir of oxygen. However, observations from the SWAS and Odin satellites proved this not to be the case, and the generally accepted theory is that in these conditions, a large fraction of the water is frozen on grain surfaces. This is consistent with observations of grain surface water ice seen in IR absorption for sources with > 4 magnitudes of visual extinction. But there are significant regions within the ISM in which gas-phase water abundance is much larger, and approaches the predictions of gas-phase models. These regions are especially valuable as probes of key portions of the overall process of star formation.

The outflows produced by Young Stellar Objects (YSOs) include swept-up, shocked material, which has been significantly heated, and in which grain surfaces have been largely "deiced". Thus, the water abundance is increased, but perhaps surprisingly, is still significantly below that predicted by models (Emprechtinger et al. 2013). The relatively strong water lines allow one to probe (with appropriate models) details of the complex physics and chemistry. This has been done for low-mass outflows by Mottram et al. (2014), using the lowest transitions of ortho- and para-H_2O.

Studying water in shocks and other high-excitation regions benefits from the widest possible range of line frequencies and upper level energies. Due to the high excitation rate, frequencies including the 1669 GHz line of ortho-H_2O as well as other lines up to several THz frequency (going well past the1900 GHz upper limit of Herschel HIFI) allow accurate determination of the total column density and determine the ortho to para ratio (e.g. Emprechtinger et al. 2013), as well as helping in disentangling multiple regimes along the line of sight.

In addition to the regions associated with star formation, "standard" diffuse interstellar medium has an impressively high gas-phase water abundance due to generally modest extinction. Observations of water absorption towards distant continuum sources has proven to be a rich source of information about the chemistry of H_2O as well as physical conditions in these regions (e.g. Flagey et al. 2012). For study of such regions, the strength of the continuum background scales almost linearly with collecting area (since sources are not resolved), and as one considers telescopes larger than Herschel, the number of lines-of-sight that can be probed increases, allowing for detailed studies of variations in such quantities as the ortho-to-para abundance ratio, which may be a tracer of the thermal history of the water molecules.

The topic of water in the ISM is the one area of this Proposal which definitely would benefit from focal plane array receivers covering a number of the water lines. Water emission is quite extended and for absorption, the background sources are all extended relative to the beam size of a plausible single-dish FIR Surveyor. Thus, the ability to probe multiple lines of sight would be significantly improved with an array. The lower-frequency water lines are in the range of proven

SIS mixer technology while the higher frequency lines will require HEB mixers. In either case, arrays of 16 – 64 pixels seem entirely reasonable from a technical point of view. The dramatic advances in digital signal processing technology mean that FFT or other backends with multi-GHz bandwidth can be envisioned requiring only a few W/pixel. Thus, multi-pixel spectroscopic imaging system deserves consideration for carrying out this science. The case may be even stronger for other areas such as fine structure line mapping, but development would be highly synergistic and the backend spectrometer could plausibly be common.

It is also plausible that higher angular resolution would be valuable for probing the structure of high-mass cores and the driving sources of outflows. While it is not clear that water observations are essential for probing these regions, tracing the water abundance in cloud cores that are the sites of high-mass star formation is clearly important in following the water trail. Thus, an interferometer with arc second or better resolution would allow study of these regions even at considerable distances. The sensitivity required would be comparable to the antenna temperature (per beam) given in the Table presented earlier in this white paper.

A-2 Water in Dense Cloud Cores

Dense cores are gravitationally bound condensations found within molecular clouds, and notably within filaments and at the junctions of filaments. New stars are also found within filaments, and the evolution of cores to stars is thus a critical step in star formation. Study of cores and combination with modeling strongly suggests that the gravitational contraction leads to formation of a protostar and disk, or of multiple star systems. An important quantity is the velocity field within the collapsing core, which is a key determinant of the subsequent behavior of the core and of the initial mass function (IMF) of the stars that are produced.

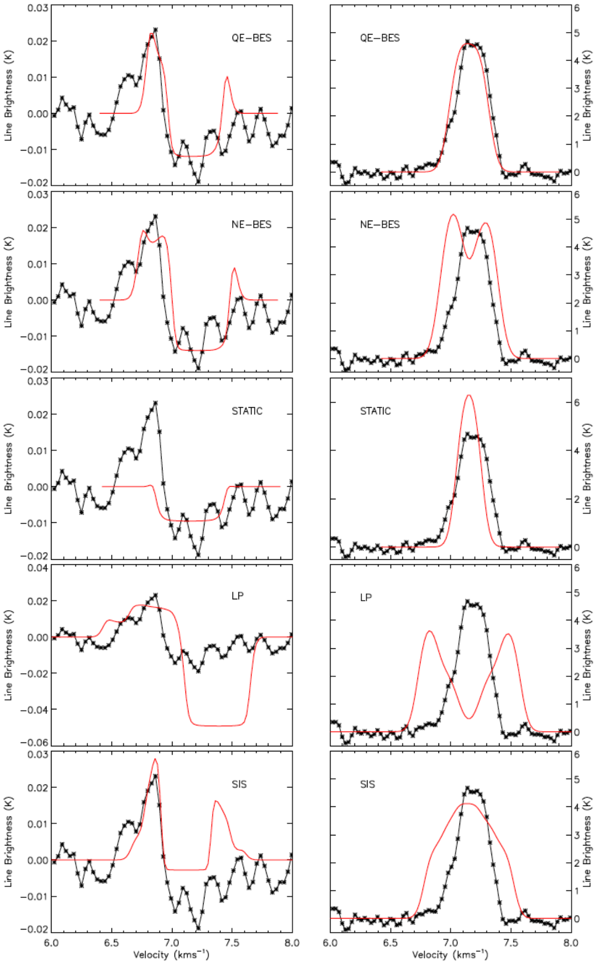

Figure A1. Observed (black & dots) and modeled (red) 557 GHz H_2O and 110 GHz $C^{18}O$ line profiles in L1544 core. Only the quasi-equilibrium Bonner-Ebert Sphere (QE-BES) is a satisfactory fit to the data. From Keto, Caselli, & Rawlings (2014); see reference for information on different velocity fields and modeling.

Different theoretical models assumed different velocity fields, but until recently, it was impossible to verify the actual dependence of collapse velocity on radius within the core. What is needed is a tracer that is sensitive to the conditions deep within the core, and which is not so abundant that the interior behavior is “hidden” by material at the boundary of the core. With observations using Herschel, Caselli et al. (2012) found a significant abundance of water deep within the L1544 dense core. The water is generally frozen as water ice on grain surfaces, but in the center of the core is kept in the gas phase by cosmic-ray produced UV photons. Only in the central region of the core is the density sufficient to excite even the lowest transition of the water molecule. The result is that the 557 GHz water line is an excellent tracer of the velocity field in the center of the core. In conjunction with CO, which probes the outer portion of the core, a real test of the different models for core collapse became possible. Keto, Caselli, and Rawlings (2014) found that ONLY the quasi-equilibrium Bonnor-Ebert sphere model was consistent with the data. This is a very significant step forward for core and star formation modeling.

L1544 is a relatively low mass core, but water has also been detected in a few high mass starless cores (P. Caselli, private communication). With the anticipated sensitivity of the FIR Surveyor being 10x that of Herschel HIFI (and effectively even greater with a focal plane array receiver), a serious survey of protostellar cores could be carried out in a few hundred hours of observing time. This would represent a landmark achievement in modeling star formation.

A-3
Technology

The sources considered here are extended on the scale of the water lines to be observed, especially if the FIRS antenna diameter is 5 m or greater. The ability to understand the distribution of the water and to measure kinematics of these regions will be dramatically increased by the availability of focal plane arrays. These are definitely viable as a result of two major technological advances

1. Improvement in local oscillator power generation means that it is relatively straightforward to pump and array of 32, 64, or 128 HEB mixers.
2. The availability of ASIC VLSI CMOS circuits for digital spectrometers means that the output of such an array can readily be analyzed with reasonable power consumption and size.

These two developments have really changed the landscape for heterodyne spectroscopic imaging in the time since Herschel/HIFI and should be considered for any heterodyne instrument being contemplated for FIRS.

Although this proposal does not address water in protostellar or protoplanetary disks, it is clear that high spectral resolution is enormously important for determining where the water is located. The ability to measure the disk rotation curve with e.g. ALMA means that a velocity-resolved spectrum can be inverted to determine the radial distribution of water. Thus, the issue of technology for the cloud and core observations discussed here is closely connected to that needed for disk studies. For disk observations, focal plane arrays are less important. Going one step further, for observations of solar system objects the situation is intermediate. With a “large” FIR Surveyor antenna, some comets will be marginally resolved, so a small focal plane array will definitely be helpful.

Additional References

Caselli, P., et al. 2012, Ap. J. Letters, 759, L37
Emprechtinger, M., et al. 2013, Ap.J., 765, 61
Flagey, N., et al. 2012, Ap. J. 762, 11